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A methodology for building energy modelling and calibration in warm climates

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Abstract

In the last 7 years, a method has been developed to analyse building energy performance using computer simulation, in Brazil. The method combines analysis of building design plans and documentation, walk-through visits, electric and thermal measurements and the use of an energy simulation tool (DOE-2.1E code). The method was used to model more than 15 office buildings (more than 200 000 m^2), located between 12.5° and 27.5° South latitude. The paper describes the basic methodology, with data for one building and presents additional results for other six cases. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Energy simulation; Commercial building; Calibration

1. Introduction

Software packages (energy tools) are generally used to assess the energy consumption of buildings. Many software are available like DOE-2, BLAST, ESP-r and ENERGY-PLUS [1]. All are based in a model representation of the building.

In principle, the model is developed to fit into a problem domain with reduced physical entities and phenomena to idealized form on a desired level of abstraction [2]. De Wit and Augenbroe [3] recognize two sources of uncertainty in the analysis of the model. The first one is denominated uncertainty parameters and relates to a lack of information on the exact characteristics of the building. The second one is the modelling uncertainty that arises from simplifications and assumptions that have been introduced in the development of the model. The question raised is how much effort and resources are necessary to produce a satisfactory model. The attempt of answer is provided with a calibration method [4]. This is the starting point for this paper, which presents a modelling and calibrating method with successive increasing levels of complexity and their impact on the results. Emphasis is laid on "input" and "output" tasks, since the software itself exists; it is well recognized and validated. The "input" aims to represent the building as an abstraction of the reality and this process determines the accuracy of the results. On the other hand, the "output" consists of reporting results of the simulations, comparing them with real-energy-use data and checking accuracy. The method was initially based on procedures reported by Kaplan [5], Haberl and Komor [6,7], Bronson et al. [8] and Corson [9]. The first proposal was presented in the master thesis of Pedrini [10], developed in the Building Energy Efficiency Laboratory (LabEEE/ UFSC/ Brazil). Since then, the method has been modified to allow variations and adapted to different building cases.

2. Methodology

The methodology can be divided into three steps:

(1) Simulation from building design plans and documentation;
(2) walk-through and audit;
(3) end-use energy measurements.

The main parameter for model acceptance is the comparison of monthly energy consumption of the real and the simulated building [11]. The phases of this process are described in the following sessions. Aiming a better understanding, some details of the process are illustrated for the Eletrosul building (Fig. 1)—the headquarters of the electrical energy supplier company for South Brazil—located in Florianópolis (latitude 27.40° South, longitude 48.33° West). The building

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Fig. 1. Eletrosul building (10 000 m^2).

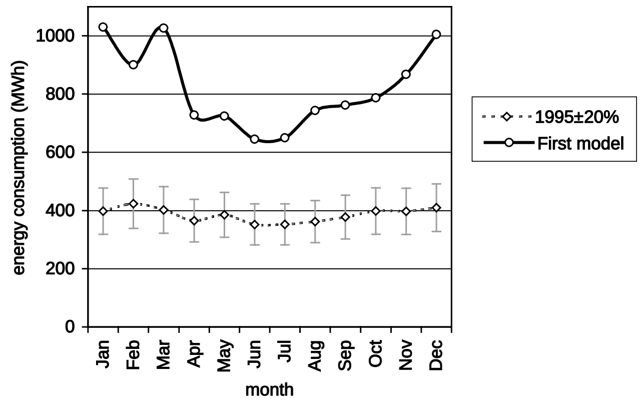

Fig. 2. First model of Eletrosul building.

has 30 000 m^2 distributed in five storeys, two underground, and was built in 1978. With 16.3 W/m^2 of light power density (LPD) and 940 tons of cooling capacity, this building presents average energy consumption of 157 kW h/m^2 year.

2.1. Simulation from building design plans

The first step involves an evaluation of the building plans and documentation, without any visit to the site. The intention is to build a model based only on existing information to estimate the building energy use. As the analyst needs no contact with the building, the distance between analyst and building is irrelevant. This is a strong advantage for countries like Brazil and Australia, due the continental distances between cities. The main source of data is:

- *Architectural plans*: used to identify geometries and layouts, construction components, window areas and others, derived from site and floor plans, sections and construction details such as roof, wall, windows and exterior shading.
- *Electric lighting system*: the information sources are electrical design plans and the nominal characteristics of lamps, ballasts and luminaries available in catalogues.
- *Air conditioning secondary system*: air distribution plan, design report with characteristics such as cooling and heating set points, supply air and exterior air flows for each zone, total and sensible cooling capacity, EER and fan nominal power and flow.
- *Air conditioning primary system*: cooling water distribution plan, chiller characteristics such as model and year, COP as well as efficiency at 100%, 75%, 50% and 25%, cooling capacity, chilled water supply temperature, cooling management, chiller schedule report (this is routinely monitored every day by operation personel).
- Total number of occupants.
- Building schedule for lighting, occupants and air conditioning.
- *Equipment inventory*: number of computers and other relevant equipment with considerable energy consumption.
- Billing history with monthly energy consumption and demand (at least 1 year).
- Hourly energy demand data for a representative period, usually available from the energy utility for large buildings.
- *Building component properties*: special features must be characterized in detail (such as windows in buildings with large window/wall ratio), which generally is available in catalogues and manuals published by the supplier.

Using all these information, the first model is built. Far too often inputs are assumed, due to lack of documentation. In this situation, a good library with appropriate defaults is extremely useful. Results of the first model usually differ from the measured monthly consumption, far from the acceptable prescribed [11] range of up to 20%. The results for Eletrosul building can be seen in Fig. 2. The annual difference between simulated and actual energy consumption was 114%. The largest difference was identified in January, with 159%, and the lowest difference in June, with 83%.

The model refinement starts with the building envelope and fabric, which are the main sources of thermal loads (peak day and integrated monthly loads). The inputs related to the highest thermal loads are analysed using parametric simulation.

The next refinement focuses on schedules calibration based on hourly energy demand. The analysis starts with the demand recorded by the energy utility company for a representative period such as one month. Fig. 3 presents the demand recorded by the energy utility company with a sample interval of 15 min. Each curve represents 1 day of the month, showing constant demand during the weekends. As the simulation tool uses hourly base calculation and presents the demand values (kW) for each hour, equal to hourly consumption (kWh), the energy utility company values are integrated to hourly base. This process is necessary to enable the comparison between the two sources of information.

In Fig. 3, it can be seen that the occupation pattern of the building, which starts at 7:00 and finishes gradually from

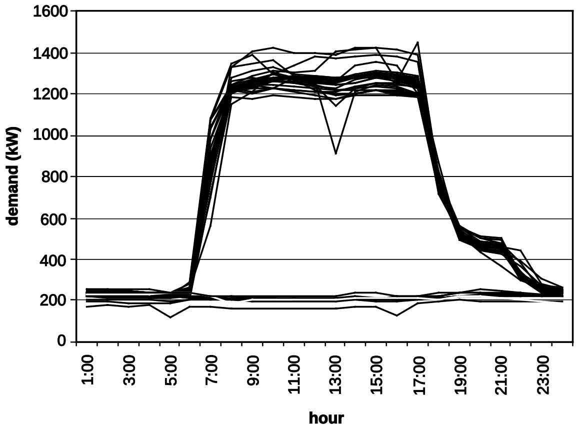

Fig. 3. Recorded demand.

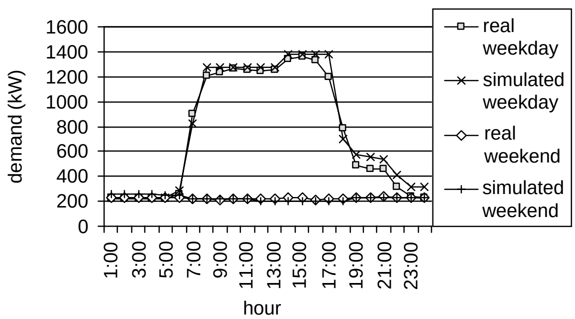

Fig. 4. Energy demand comparison: simulated x real.

17:00 to 19:00. From 19:00 to 23:00 the cleaners maintain a part of the lighting system on. During the weekdays night—23:00 to 6:00—and the whole weekends, only the 24 h equipments (computer services) are operating.

From the energy utility company files, the typical days are generated to enable the schedule calibration. Fig. 4 presents the Eletrosul demand curves estimated by the simulation tool and the average curves calculated from the energy utility company files. In this case, the weekend is represented by a single curve, because the occupation on Saturdays is the same as Sundays.

After schedule adjustment, the calibration of Eletrosul building presents better results, as can be seen in Fig. 5. At this stage, the annual difference between simulated and actual energy consumption was 5.6%. The largest difference was identified in June, with 19.1%, and the lowest difference in December, with 1.0%.

2.2. Audit stage

The second step is referred to as "Walk-through and audit phase". Using observations derived from the previous step, the analyst visits the building with a technician, who must be familiar with the operation of the building. With building plans and some colour pens, the analyst classifies the zones following criteria such as type of use, artificial lighting and climate control. Generally, those areas attended by the same air-conditioning system are grouped into a zone. The unconditioned areas would be represented with a different colour. Zones with a singular schedule, such as a restaurant, would be represented with another colour. Whenever possible, the analyst must confirm information about use, questioning the users, cleaners that normally work after-hours, and system operators. The time spent in modelling will be reduced if all information for each zone is listed in the building plans.

During the visit, some measurements must be carried out. The first ones are instantaneous measurements using hand-held instruments (Fig. 6) to check lighting levels, airflow, air temperature, active power in circuits of equipments and artificial lights. Frequently, nominal values for lighting power differ from the real ones, especially with discharge lamps operating with ballasts. This must be followed by measurements over periods of days or weeks with data loggers (Fig. 6).

Pocket temperature data-loggers are installed close to the air return in fan-coils chambers measuring the average

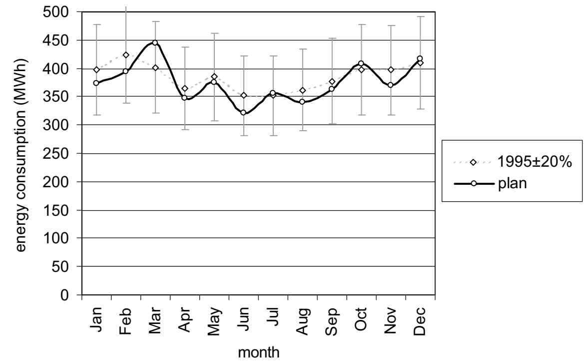

Fig. 5. Calibration of the Eletrosul building in the first step (simulation from building design plans and documentation).

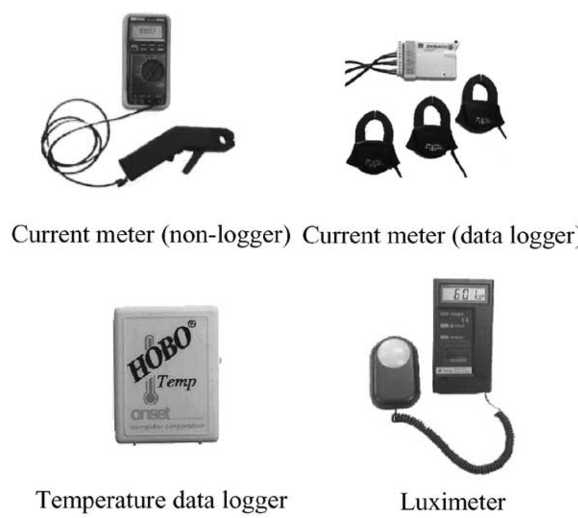

Fig. 6. Hand-held and very small data-loggers instruments available in LabEEE.

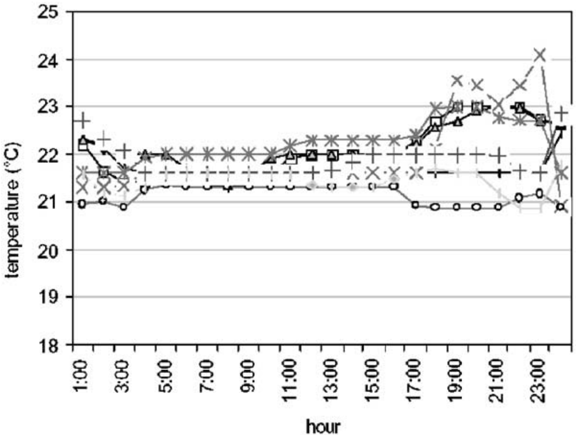

Fig. 7. Temperature monitoring for different office rooms.

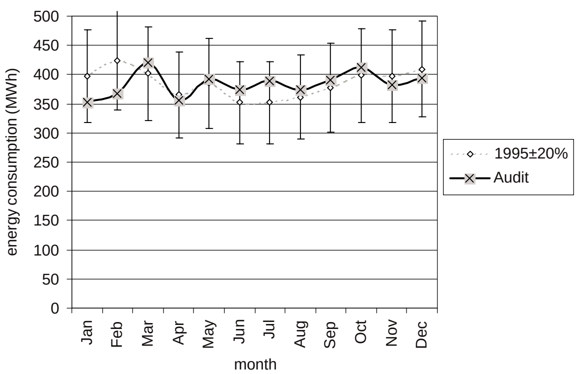

Fig. 8. Second calibrated model, after the walk-through and audit stage.

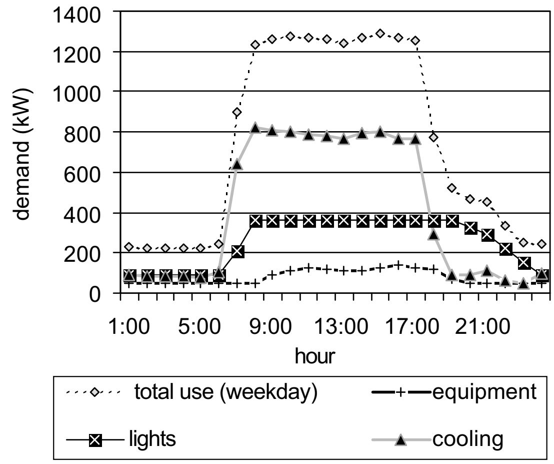

Fig. 9. Total and end-use energy demand.

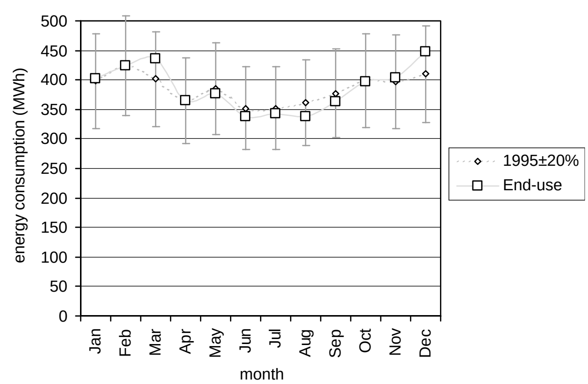

Fig. 10. Third calibrated model: end-use stage.

temperature of the zones. The recorded data provide average profiles (Fig. 7) that derive the cooling set point schedule and additional information such as load not met. Furthermore, the data can indicate the time that the fan coils are switched on and off and consequently indicate the hours of occupation. Fig. 7 presents temperature profiles for different days in a computer service room. The constant temperature (approximately 21.5° C) between 4:00 and 17:00 represents the fan-coil schedule.

The results obtained in this phase are used to tune inputs such as LPD, equipment power density, cooling set point and schedules. The new calibrated model is shown in Fig. 8. The annual difference between simulated and actual energy consumption was 0.1%. The largest difference was identified in February, with 13.3%, and the lowest difference in May, with 1.7%.

2.3. *End-use phase*

The third step consists of splitting the measurement into energy end-use by lights, equipments (plug-in type) and air-conditioning circuits, as showed in the Fig. 9. Usually, these measurements can be done in the transformer or main switch room, if the electrical system is sufficiently refined and organized to identify circuits for each purpose. In all buildings studied, the circuits were mixed due to years of maintenance and layout changes by non-specialized professionals.

The results from end-use monitoring are used for tuning the schedule and internal power density (equipment and artificial lighting), which produced a calibrated curve 0.2% higher than the reference (Fig. 10). The largest difference was identified in December, with 9.2%, and the lowest difference in April, with 0.2%.

Although the improvement in total annual energy consumption is not high, the changes in end-use are significant.

3. Conclusions from Eletrosul building

All phases successively increase the model accuracy and the influence of each one depends on the quality of information and the building type. In each step, the simulated results were close to the total real consumption (19.1% maximum difference in phase one, 13.3% in phase two and 9.2% in phase three). Using the end-use energy reports for each model of the Eletrosul building (Fig. 11), it can be seen

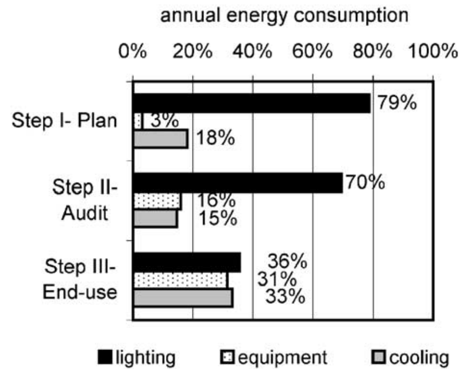

Fig. 11. End-use energy for different levels of modelling.

an overestimation of lighting energy consumption, which decreases with the refinements of the model. On the other hand, plug-in equipment and HVAC are underestimated in the first model and successively increase in proportion. The main improvement is obtained by the energy end-use determination (third phase).

4. Additional cases

4.1. Six cities project

In order to help the development of energy efficiency building standard in Brazil, to demonstrate state-of-art technologies and to encourage the use of hourly building simulation programs, PROCEL (Brazilian Electricity Conservation Program) started the "Six Cities Project" in 1996 in collaboration with UFSC/LabEEE [12]. The project was developed in six cities around the country with a standard methodology, which was developed and applied for commercial and public buildings. The six cities chosen were: Florianópolis, Curitiba, Rio de Janeiro, Belo Horizonte, Brasília and Salvador. One stage of the research was the retrofit proposal using computer simulation as analysis tool applying the methodology presented in this paper. The software chosen for this task was the VisualDOE, which is a friendly interface to DOE-2.1E. The LabEEE provided the training in building simulation for each city research team. Two buildings were selected for analysis (modelling, calibration and retrofit proposal) in each city. Four buildings of this project will be described here: two in Florianópolis and two in Salvador. Two others building simulated (not part of Six Cities Project), located in Rio de Janeiro and Brasília, will also be described. Fig. 12 presents the geographic location of the cities under analysis.

4.1.1. TELESC building

The TELESC building (Fig. 13), located in Florianópolis ($27^{\circ}40'$ South latitude), was the first case modelled after Eletrosul applying this methodology. The TELESC—headquarters of the Telecommunication Company of the

Fig. 12. Location of simulated buildings.

Fig. 13. TELESC, Florianópolis.

State of Santa Catarina—has 10 250 m^2 distributed in three storeys and was built in 1976. With 23.0 W/m^2 of lighting power density and a central air-conditioning system with 240 tons of cooling capacity, the building consumes about 313 kW h/m^2 year. The building presents a "Y" shape, with WWR about 40% and all windows have exterior shades, as can be seen in Fig. 13.

As the building was located close to the LabEEE, the first step of the methodology was not necessary. The modelling started with the walk-through and audit phase. The main difficulties appeared during the monitoring activities. As the analysed building was 20 years old, the available design plans did not match with the actual installations. In several parts of the building, the plug-in circuits were mixed with lighting circuits and the end-use measurement in the main switch room was not possible.

In the last years, building internal loads have been increased substantially. Nowadays, there is a personal computer for each occupant and a central computer was installed in the building. The original air-conditioning system is outdated and unitary systems were installed around the first storey in order to supply the additional cooling loads.

The calibration of the model started with the lighting system assessment in the audit phase. In this phase, all fixtures,

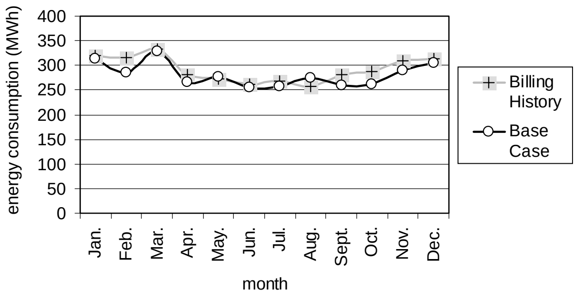

Fig. 14. Calibrated model for TELESC building.

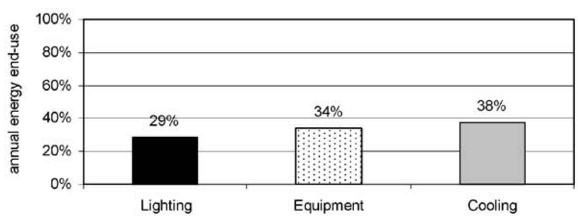

Fig. 15. Energy end-use for TELESC building.

Fig. 16. FIESC, Florianópolis.

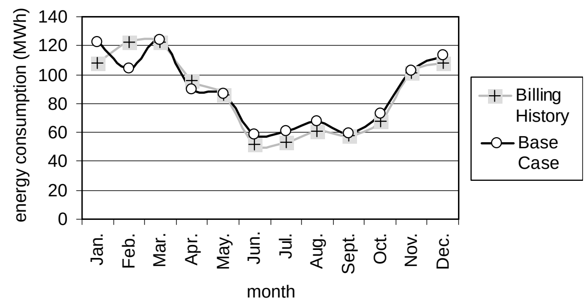

Fig. 17. Calibrated model for FIESC building.

lamps and ballasts were counted. The total lighting power was obtained multiplying the number of lamps and its nominal power plus the ballast power. The calibration was concluded after the measurement of chillers, fan-coils and cooling towers energy consumption during 2 weeks in the summer. The cooling towers and fan-coils power was defined by short-term measurement (a few hours). The chillers energy consumption was measured during the 2 weeks of monitoring. The plug-in equipments power was obtained by difference between the total demand and the lighting, chillers and fan-coils power.

Fig. 14 shows the calibrated model for TELESC building. The annual difference between simulated and actual energy consumption was −3.7%. The largest difference was identified in February, with −9.8%, and the lowest difference in March, with −1.3%.

The energy end-use in TELESC building is presented in Fig. 15. The high equipment power density corresponds to 34% of the annual electricity consumption. The central computer room, operating 24 h a day, contribute considerably to the participation of the equipments in the annual consumption, decreasing the lighting end-use, which is switched off during the night.

4.1.2. *FIESC building*

The FIESC building (Fig. 16)—Headquarter of the Federation of Industries of the State of Santa Catarina—is located in Florianópolis, has $10\,900\ \mathrm{m}^2$ distributed in four storeys and it was built in 1983. With $16.4\ \mathrm{W/m}^2$ of lighting power density and a central air-conditioning system with 480 tons of cooling capacity, the building consumes about $103\ \mathrm{kW\,h/m}^2$ year. The building presents a square shape, with WWR about 45% and all windows have exterior shades with 1.25 m between windows.

As in the TELESC building, the modelling of the FIESC starts in the second step of the methodology (audit phase). The modelling started with the lighting system assessment, following by cooling towers, fan-coils and chillers energy consumption measurement. For this building, as the air conditioning system is totally shut off in the winter (July and August), the energy end-use identification was more easy. The difference between the energy consumption registered in the summer months and in the winter months could be considered as the energy consumed by the air-conditioning system.

The automatic system that controls the central plant was damaged and the operators controlled even the cool water temperature manually. Thus, the greatest difficulty was the calibration in the spring and autumn months, when the operators switch on the air conditioners manually on demand depending on users wishes.

Fig. 17 shows the calibrated model for FIESC building. The annual difference between simulated and actual energy consumption was 2.7%. The largest difference was identified in July, with 15.1%, and the lowest difference was noticed in May, with 0.8%. The higher consumption in summer months than in winter months follows the cooling degree-hours trend for Florianópolis city, presented in Fig. 18 for three base temperatures: 24°C, 25°C and 26°C [13].

The energy end-use in FIESC building is presented in Fig. 19. The lighting system is the main end-use followed by air-conditioning system and others equipments.

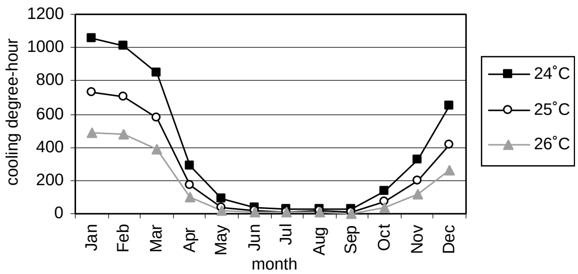

Fig. 18. Cooling degree-hours for Florianópolis city.

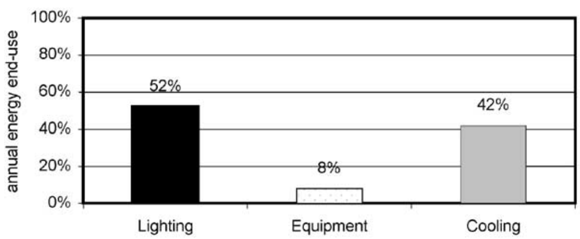

Fig. 19. Energy end-use for FIESC building.

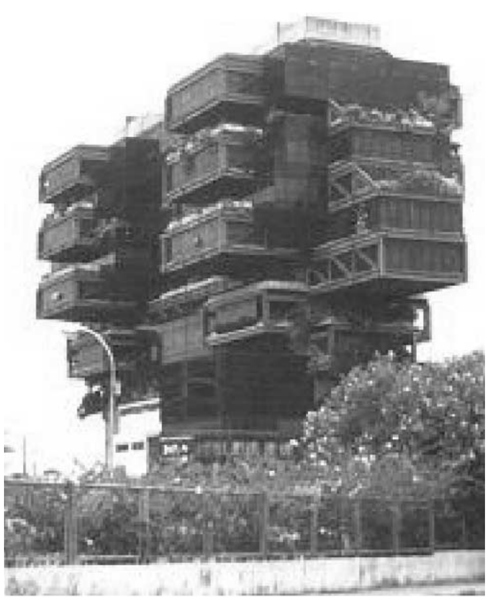

Fig. 20. SESC, Salvador.

4.1.3. SESC building

The SESC—Brazilian Commerce Social Assistance—building is located in Salvador (12°54′ South latitude) and was built in 1988, with 16 431 m^2 of constructed area. The SESC building incorporates a modern architecture design, with full glazed facades, as seen in Fig. 20. There are offices, schoolrooms, restaurant and theatre in the building, with a different operation pattern for each one.

The building was first modelled in 2 weeks, followed by a short visit to the site. The highlight of the process is the intense use of energy end-use recordings produced by COELBA (local energy utility) technicians. The HVAC

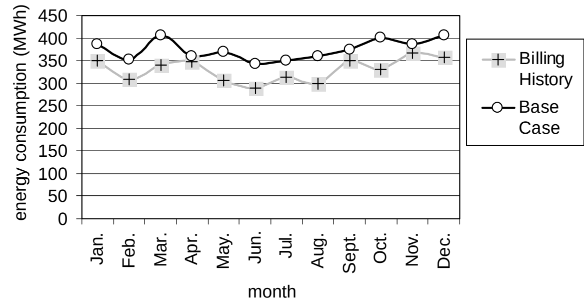

Fig. 21. Calibrated model for SESC building.

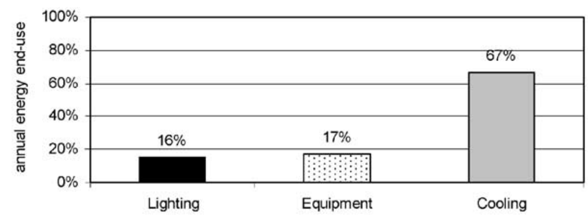

Fig. 22. Energy end-use for SESC building.

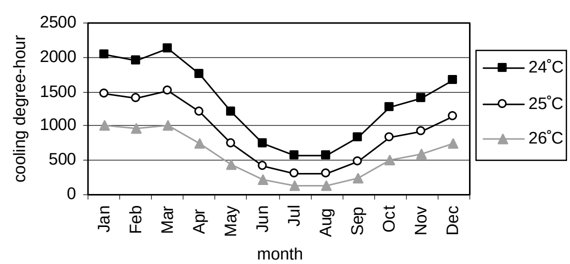

Fig. 23. Cooling degree-hours for Salvador city.

calibration was simplified due to lack of documentation of chillers operation. The final model is presented in Fig. 21. The annual difference between simulated and actual energy consumption was −11.9%. The largest difference was identified in October, with 17.5%, and the lowest difference in April, with 3.3%.

The main energy end-use for SESC building is the HVAC system, with 67% (Fig. 22), confirming the effects of the architectural typology presented by the building, with full-glazed facades, and the hot climate of Salvador city. The use of air-conditioning system during the whole year generates constant monthly energy consumption, as shown in Fig. 21.

The cooling degree-hours for three base temperatures for Salvador city are presented in Fig. 23 [13].

4.1.4. COELBA building

The COELBA—Electrical Energy Utility Company for the State of Bahia—located in Salvador, was built in 1981, has 15 000 m^2 and is fully air-conditioned (Fig. 24). As the SESC building, the COELBA building presents full-glazed facades, which reflects on intensive use of the HVAC system.

Fig. 24. COELBA building, Salvador.

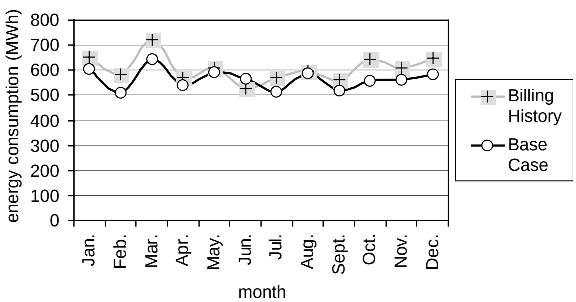

Fig. 25. Calibrated model for COELBA building.

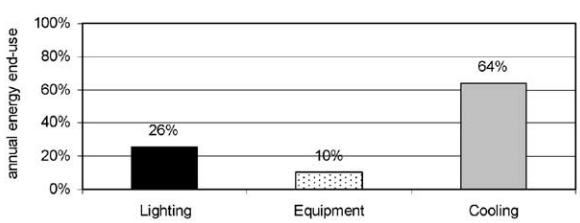

Fig. 26. Energy end-use for COELBA building.

The first step of the methodology was not applied and the modelling and calibration were developed during a one-week visit and audit. The inputs of the model were entered using a PC inside the building; in this way, any doubt about building operation or energy measurement was immediately solved with total cooperation of COELBA employees. The final model is presented in Fig. 25. As in the SESC building, monthly consumption is constant, since the HVAC is used all year. The annual difference between simulated and actual energy consumption was 7.6%. The largest difference was identified in October, with 15.2%, and the lowest difference in August, with 1.8%.

The main energy end-use for COELBA building is the cooling system, representing 64% of the annual electric energy consumed Fig. 26. The lighting system is the second end-use with 26% and others equipments correspond to 10% of the building energy consumption.

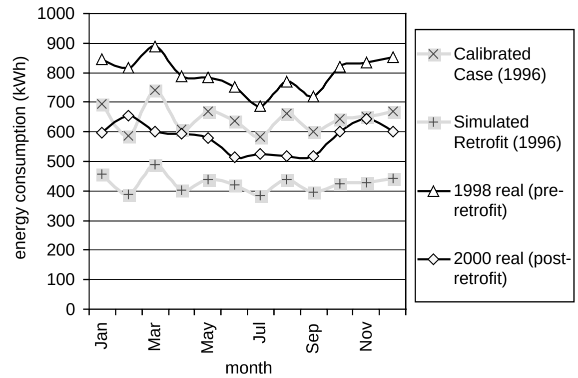

Fig. 27. Comparison of predicted savings and achievements.

Fig. 28. Central Bank of Brazil, Brasilia.

The energy diagnostics led to the study, design and implementation of retrofit, as shown in Fig. 27. Since the building modelling (1997), the building occupancy increased as well as the energy consumption (curve 1998-real). The predicted energy savings based in 1996 was 34% and the savings achieved in 2000 was 28%.

4.2. Other cases

4.2.1. Central bank of Brazil

The Central Bank building (Fig. 28), located in Brasília ($15^\circ 52'$ South latitude), was modelled in 4 months and only two visits to the site were necessary to generate the calibrated model. The envelope thermal characteristics, the large area ($100\,000$ m^2) and the complex electric diagram produced many models that reached the VisualDOE limits, such as number of zones, façades and windows.

The chillers were calibrated based on temperature and electric current records for a long period. The end-use

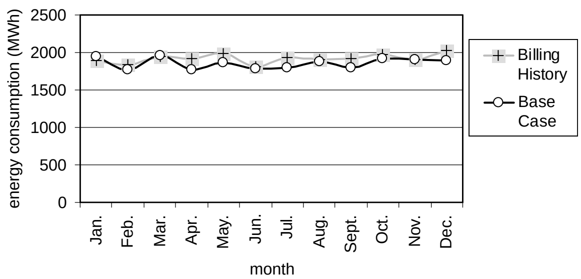

Fig. 29. Calibrated model for Central Bank building.

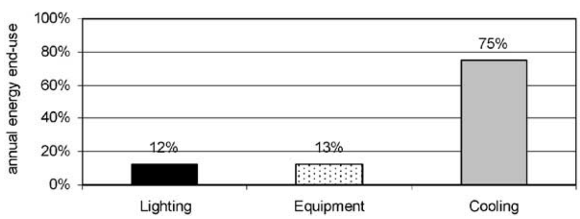

Fig. 30. Energy end-use for Central Bank building.

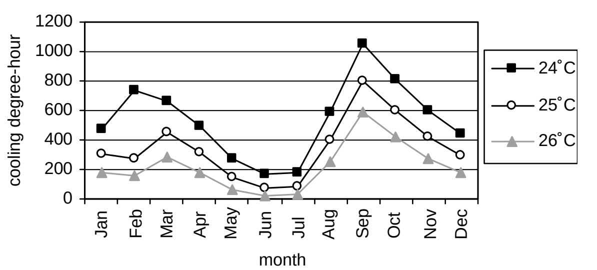

Fig. 31. Cooling degree-hours for Brasília city [13].

monitoring was facilitated by the organization in the main switch room: the building has three transformers, one for each end-use (lighting, air-conditioning and plug-in equipments). At the end, the calibrated model had 3.5% of difference in relation to reality (Fig. 29). The largest difference was identified in April, with 8.6%, and the lowest difference in March, with −0.4%.

The effect of the full-glazed façade of the Central Bank building is noticed in the energy end-use analysis: 75% of the annual energy consumption is related to air conditioning system (Fig. 30). The others end-use, lighting and plug-in equipments, corresponds to 12% and 13% of the annual consumption, respectively.

The cooling degree-hours for Brasília city is presented in Fig. 31 for three base temperatures [13]. It can be seen that the artificial conditioning is necessary even in the moderate seasons, such as in June and July months. The bad thermal performance of the building envelope forces the building operators to switch on the air conditioner at 4:00 in Mondays in order to remove the thermal load accumulated during the weekends.

Fig. 32. FURNAS, Rio de Janeiro.

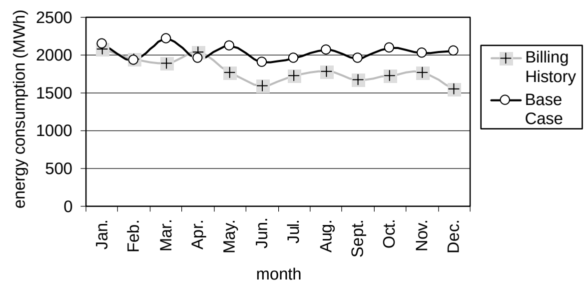

Fig. 33. Calibrated model for FURNAS buildings.

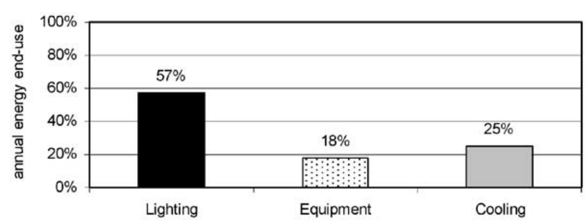

Fig. 34. Energy end-use for FURNAS buildings.

4.2.2. FURNAS building

The headquarters of FURNAS Electrical Company S/A (Fig. 32) consists of four towers adding 69 000 m^2 and is located in Rio de Janeiro (22°50′ South latitude). The total cooling capacity of the air conditioning system is 2675 tons distributed into two central plants. The annual electric energy consumption corresponds to 298 kWh/m^2 year.

The buildings were modelled in Florianópolis (phase one). During the audit phase, a group of FURNAS engineers was trained in a 1-week course. This group participated in the third and fourth phases of the modelling also as in Fig. 33.

The billing history (1998) used for calibration of the model presented a significant reduction of the consumption after the June month, because changing in schedules and occupation of the buildings. Then, the group of engineers decided to calibrate the model with the more conservative data, before June.

The energy end-use for FURNAS buildings is presented in Fig. 34. The lighting system is the main end-use, representing 57% of the annual consumption, followed by air-conditioning system (25%) and others equipments (18%).

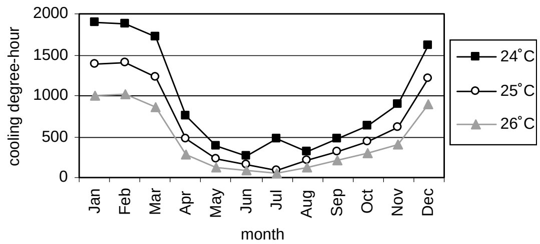

Fig. 35. Cooling degree-hours for Rio de Janeiro city.

Analysing the cooling degree-hours for Rio de Janeiro city (Fig. 35), a higher consumption for cooling end-use would be expected, what was not verified in Fig. 34. The low energy use by the air-conditioner system is justified by the high-efficiency central plants installed in the buildings and low WWR. 86% of the cooled water is supplied by four centrifugal chillers (high efficiency), while only 14% is supplied by reciprocating chillers (low efficiency).

5. Conclusions

Model calibration is an important issue in retrofit studies. The methodology of model calibration presented here is divided into three stages, with different levels of information details and accuracy. The results obtained in each stage and the gains in accuracy are clearly shown in the Eletrosul building. The first model presented a simulated annual electric energy consumption 114% higher than actual consumption. The second model, with a better description of the building zones obtained during the building audit, has decreased the annual consumption difference to 0.1%. The third phase (end-use) shows a similar difference in the annual consumption (0.2%) but the energy end-use of the building was adjusted to real figures allowing better retrofit studies.

In all commercial buildings simulated, the schedules description has been the most significant stage in model calibration, and utility demand data recorded every 15 min in digital form is a very good resource of information. For commercial buildings, with high-internal loads, occupation and operation patterns have significant influence on the annual energy consumption. In this context, measurements of energy consumption by end-use have great impact on adequate end-use modelling.

Because of the complexity of the thermal processes occurring between building, environment and internal loads, most simulation software present non-friendly interfaces with a lot of inputs, requiring multidisciplinary knowledge. A good set of default values adjusted to typical buildings, and a sensitivity tool embedded in the simulation software could help the energy analyst during the calibration, helping in the measurement plans and pointing the variables with higher impact on building energy consumption.

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